FINAL TECHNICAL REPORT

Award # 06HQGR0135

GEOTECHNICAL ARRAY DATA ANALYSIS AT BORREGO VALLEY AND NEES/ANSS INTEGRATION

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ABSTRACT:
A significant component of the research efforts at the Institute for crustal studies (ICS) are centered around understanding the physics of the earthquake process and the effects of earthquakes on the built environment. These require not only computational facilities for doing theoretical modeling of wave propagation and earthquake source process simulation, but also field observatories for monitoring earthquake activity. These field observatories provide the control data for testing our theoretical models and simulation techniques, so we can determine if our models are matching real observations of earthquakes. One of these field observatories is the Borrego Valley Downhole Array (BVDA), located just north of the town of Borrego Springs, CA. This observatory, donated to ICS by the Japanese firm Kajima Engineering and Construction Corp. is now integrated into the National Science Foundations George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) program, through the multi-agency collaboration with the US Geological Survey that was facilitated by this NEHRP external program award.

Figure 1. The Borrego Valley Downhole Array Facility

In the spring of 2007 through funding under this USGS program, the BVDA site was upgraded with a Kinemetrics, Inc. Marmot field processor and VPN network router that allowed the site to be integrated into the NEES@UCSB data acquisition and processing infrastructure. Continuous data from the BVDA site now flow in real-time to UCSB and is archived. In addition, routine processing which segments out events from the continuous data stream for the NEES field sites is also now set up for the BVDA station. Automated data analysis of each event waveform provides peak acceleration, peak velocity, and signal to noise ratios for each record. Through the NEES@UCSB program, we have also been developing web-based applications for state-of-health monitoring and data dissemination tools for all the instrumented geotechnical field sites. The BVDA site has now been integrated into these online processing and analysis tools.

Background: The Borrego Valley Downhole Array

In 1993, Kajima Engineering and Construction Corp. and Agbabian Associates established the Borrego Valley downhole array (BVDA) near Borrego Springs, in Southern California. In this array there are four borehole instruments extending depths of 9, 19, 139 and 238 m. In addition, BVDA has 15 surface instruments extending in two directions across the Borrego Valley, and a remote rock site at the edge of the valley that includes surface and borehole sensors (Figure 2). At the main station data acquisition systems building the shear wave velocity gently increases from about 300 m/s at the surface to 750 m/s at 230 m—the granite interface—where it jumps to 2500 m/s (Table 1). The water table is at ~92 m depth; BVDA is representative of a dry site in NEHRP site class C.

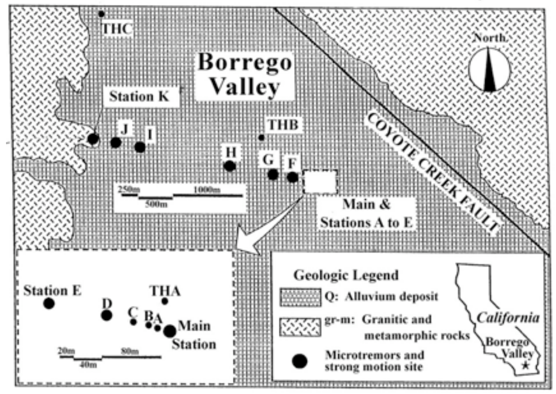


Figure 2. Schematic diagram showing layout of Borrego Valley downhole array.

In Figure 3 we show observations of an M 2.4 earthquake at a distance of 7.3 km recorded at BVDA. In addition to the records of the vertical array at the main station, the records from the rock outcrop at station K (Fig. 2) are shown. The soil structure clearly amplifies the motion. Note that the scale is the same for each accelerogram. Amplitudes at the rock outcrop are equal to or larger than those at the surface of the soil site, suggesting that the rock outcrop has also amplified the motion. Even dividing by a factor of two we can see that the rock outcrop is still clearly larger than the motion at 238-m depth. This is a clear example of a surface rock station having its own site response. Due to the observed amplification at the remote rock station, a borehole was drilled and logged at station K to characterize the rock outcrop station. S-wave velocity remained between 400-600 m/s to a depth of 25 m where slightly more competent rock was encountered. A borehole sensor is installed at station K at a depth of 30 m. In order to try and obtain a better "rock" borehole station near the remote rock outcrop site without drilling on difficult topography, station J was also drilled, logged, and instrumented. At station J, the transition from sand to decomposed granitic rock ($V_S \approx 1300$ m/s) occurs between 50 and 60 m. A borehole sensor is installed at station J at a depth of 91 m.

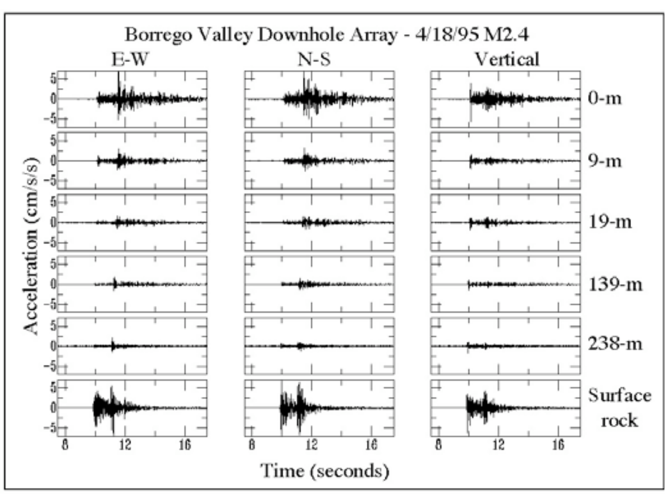


Figure 3. Observed ground acceleration at select sensors within the Borrego Valley downhole array.

In addition to the seismic instrumentation the BVDA main station has extensive site characterization data available, including geophysical logging, soil sampling, SPT tests, and dynamic laboratory testing. The rest of the valley has been investigated in detail to provide structure for 3D simulation (Martin, 1999, Olsen et al., 2000). Figure 4 shows a 2D cross section of the valley with station locations, the variability in depth to basement, and water table depth shown. Geophysical measurements including gravity and magnetic surveys, and seismic refraction profiles across the valley floor are part of the investment that has previously been made in the detailed characterization of this test site. These data when combined (Martin 1999) provide the detailed 3D structure for the valley shown in Figure 5.

Table 1: BVDA Velocity Structure

Depth	Thick.	Vs	Vp	Density
(m)	(m)	(m/s)	(m/s)	(kg/m^3)
0.0	5.0	300	500	1723
5.0	10.0	400	600	1723
15.0	15.5	450	750	1723
30.5	38.5	550	900	1814
79.0	13.0	600	1050	1814
92.0	33.0	650	1900	1905
125.0	17.0	700	2100	1905
142.0	33.0	650	2100	1905
175.0	7.0	850	2350	1996
182.0	48.0	750	2200	1996
230.0		2500	3700	2086

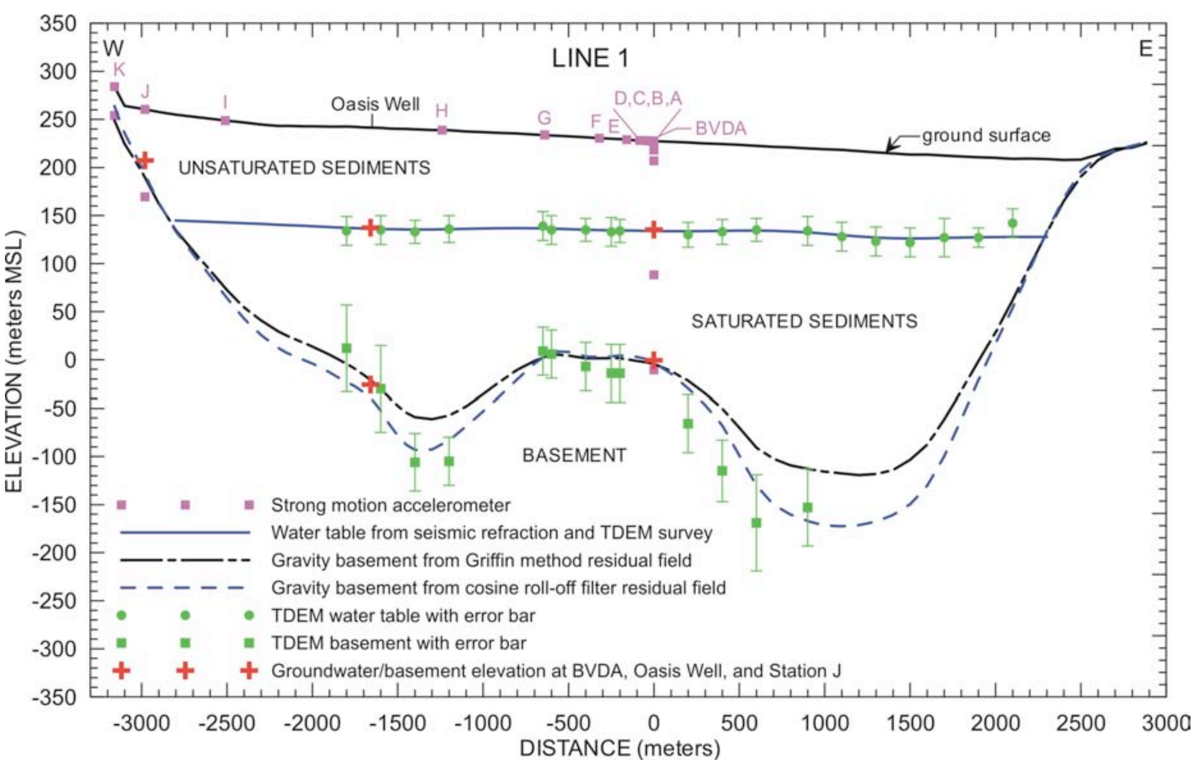


Figure 4. Cross-section of Borrego Valley showing seismic stations, depth to basement, and water table (Martin, 1999).

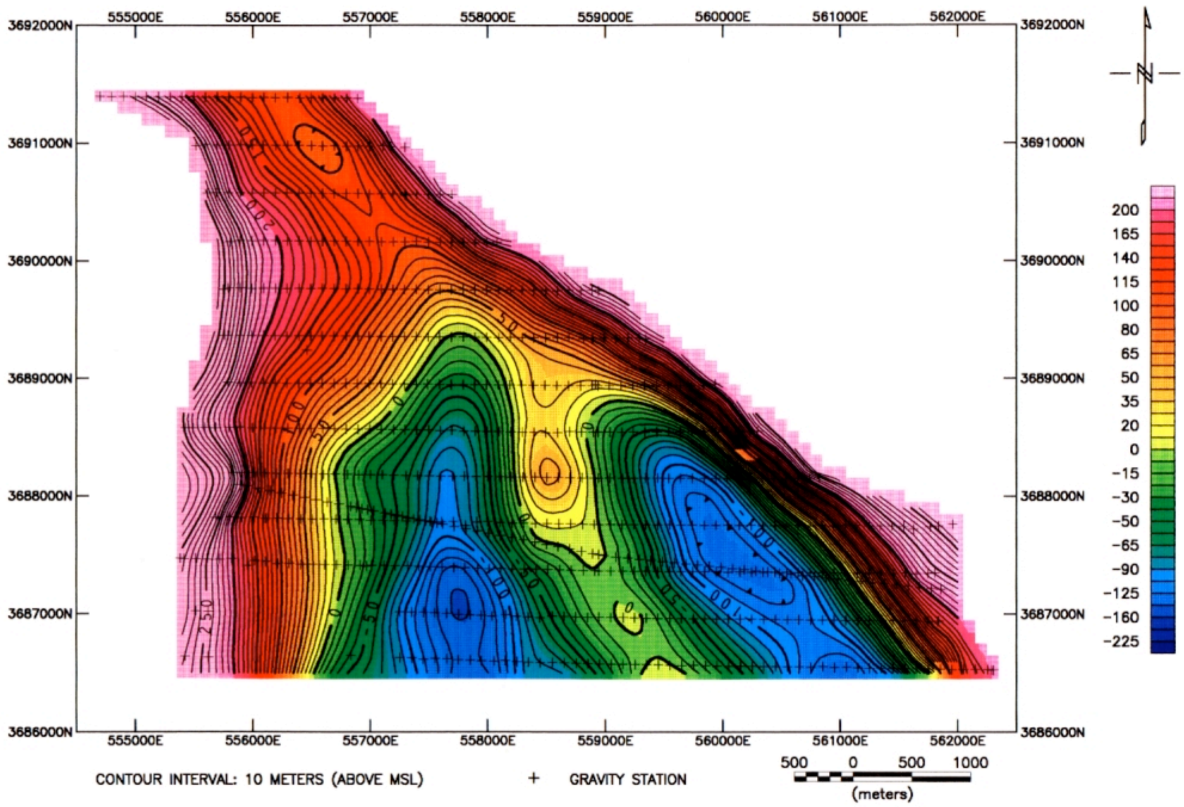


Figure 5. Contours of basement depth in the upper Borrego Valley showing the irregular 3D structure (Martin, 1999).

Project Deliverables and Results:

A primary focus of this project was to upgrade the BVDA field site and integrate it into the acquisition, processing, analysis, and data dissemination tools that are part of the NEES permanently instrumented field site program at UCSB. The upgrade included the deployment of a Kinemetrics Marmot field processor, running Linux and the Antelope software that enables the local buffering of continuous data, and real-time streaming of data back to UCSB. Figure 6 shows the installed Marmot field processor at BVDA.

Figure 6. Kinemetrics Marmot Field Processor installed at BVDA.

The addition of the Marmot field processor at BVDA allows for buffering of about 9 days of continuous data on solid-state flash. Any telemetry outage less than 9 days is automatically recovered from with no human intervention as part of the normal operations using the Antelope software package. In addition to the buffer provided by the Marmot, a daily cron job runs on the Marmot that automatically powers a network attached storage device (NAS), and copies the contents of the data buffer from the previous day onto the NAS hard drive. This drive has the capacity to hold over a full year of continuous data.

One advantage to having real-rime communications and data delivery is the ability to monitor the state of health of data acquisition equipment at the site, and the functionality of the sensors. The harsh environment in the Anza-Borrego desert can produce extreme temperatures and being able to monitor the power and cooling at the site is important (Figure 7).

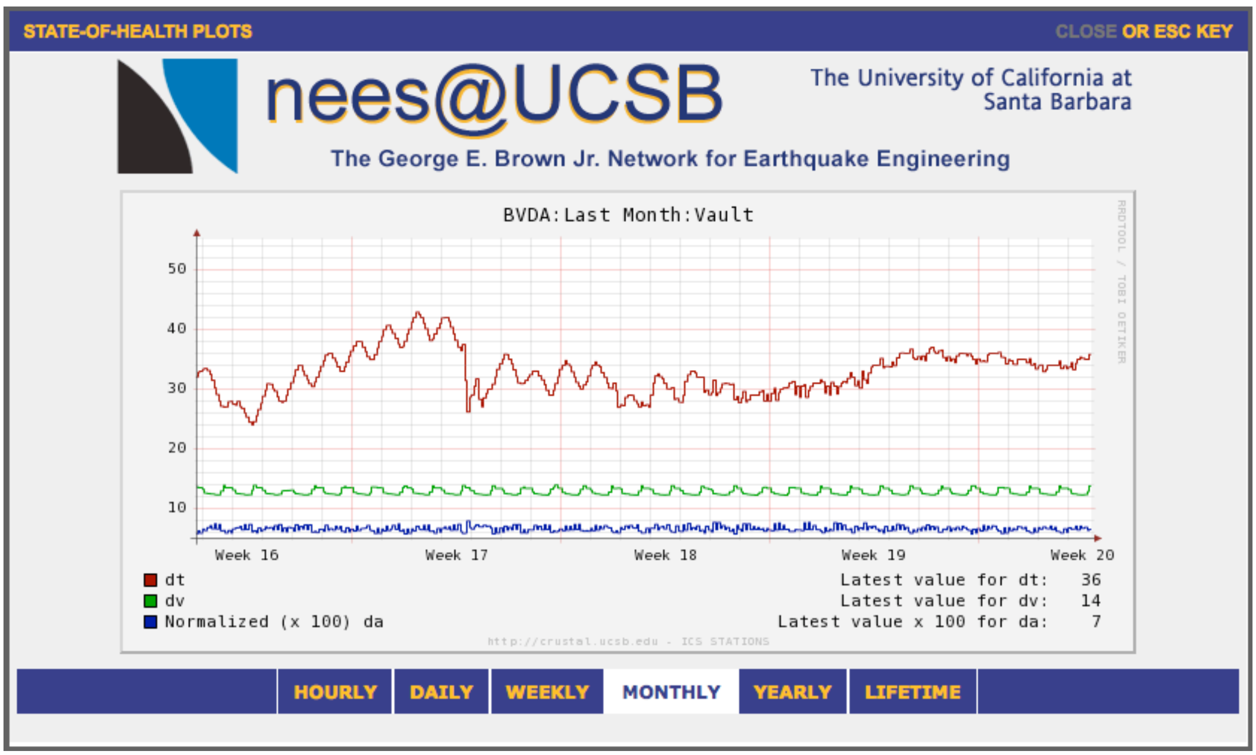


Figure 7. Screenshot showing the incorporation of the BVDA site into the NEES@UCSB web-based site monitoring tools. Station state-of-health parameters such as power and temperature are provided through a web-accessible interface. [http://nees.ucsb.edu/facilities/dlmon]

Data processing developments made possible through the NEES@UCSB program provide web-based access to state-of-health information about each of the permanently instrumented field sites. Figure 7 is an example of the temperature, power supply voltage, and current usage at the BVDA site for a 1-month period as recorded by the data acquisition system. This web-based interface allows users to access information at a variety of time scales including hourly, daily, weekly, monthly, yearly, or lifetime of the station. As the BVDA site operates exclusively on solar power, in the summer months when the temperatures outside can exceed 45°C, the excess solar energy is used to operate a cooling system. In Figure 7 you can see the change in temperature profile at around week 17 (red line) when we begin to use the cooling system. The variability in the temperature profile from this point shows the process of finding the optimal cooling cycle within the limitations that we can only run the cooling for about 2 hours total each day. Having the ability to quickly look at the state-of-health history via the web browser is extremely helpful in fine-tuning the station operations.

The ability to observe waveforms from any of the sensors in real-time provides us with a constant functionality check on the status of the sensors. A real-time 24-hour display of all sensor channels back at UCSB lets us quickly know if there are problems with a datalogger, sensor, or individual component.

The routine processing and analysis of data from the NEES@UCSB field sites includes the segmenting out the earthquake waveforms from the continuous data using a distance scale based on magnitude range. Small events are segmented out only when they occur close to the site, as the events get further from the site, a larger magnitude is required before the event will qualify to be segmented out of the continuous database. We use the ANSS catalog of earthquakes (which includes regional network determined magnitudes and locations) in this process of creating the segmented event waveform database. The BVDA site is now included in this routine data processing that was developed under the NEES program.

In addition to the automated segmenting of data from the BVDA site, earthquake waveforms are examined periodically to ensure functionality of the sensors. The event data is stored in an online database at UCSB using a RAID storage system that allows for instant access to these records. Figure 8 is an example of an M3.0 event recorded at 15km from sensors within the vertical accelerometer array at BVDA. These accelerometers are a combination of older FBA23 and more recent FBA Episensor technology, capable of recording earthquakes from M1.0-3.0 depending on proximity and sensor type, all the way up to +/- 2g accelerations from large sources in the near field. In addition to the vertical array data at the BVDA site, there is also a surface array that spans the valley. This array is operated in remote trigger mode, and is not part of the real-time system. Part of the main station array is also operated in triggered mode using an 18-channel Kinemetrics Mt. Whitney system. This system is set to trigger at approximately 20 cm/s^2 accelerations, and when this happens, the data is automatically integrated into the real-time data stream and all of the same data processing threads are applied to get the data into the event waveform database.

One of the goals of the NEES@UCSB facility is to improve data dissemination from geotechnical array sites. Over the last few years, a web-based dissemination tool has been developed to help increase the number of researchers using this data. The idea is to make the segmented event database searchable, and the waveforms accessible, via an online data portal. This process is now almost completed, though development continues as we get feedback from users. The BVDA data has been integrated into this data dissemination tool as shown in Figure 9.

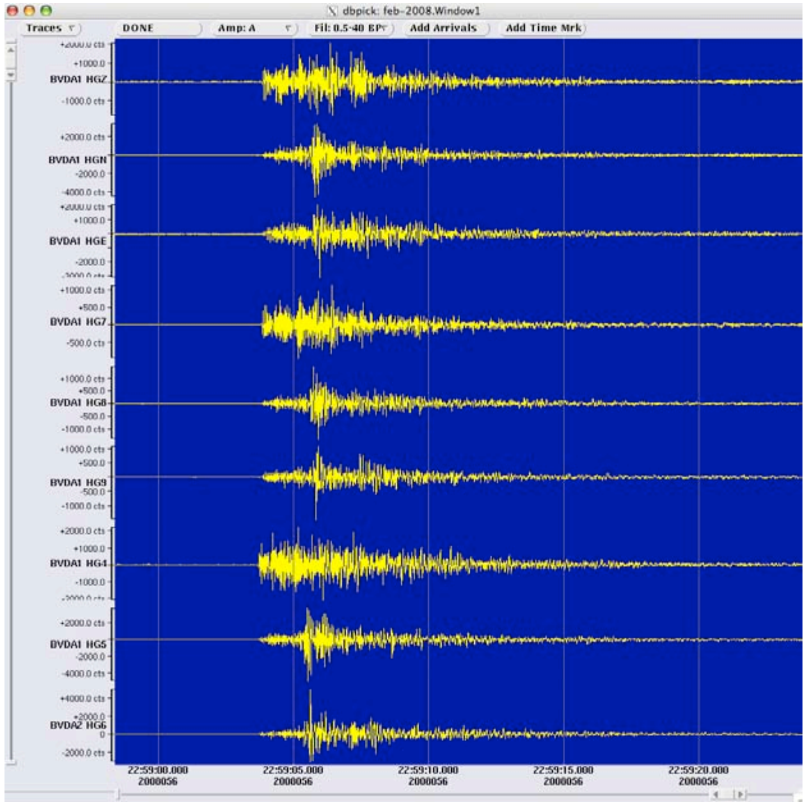
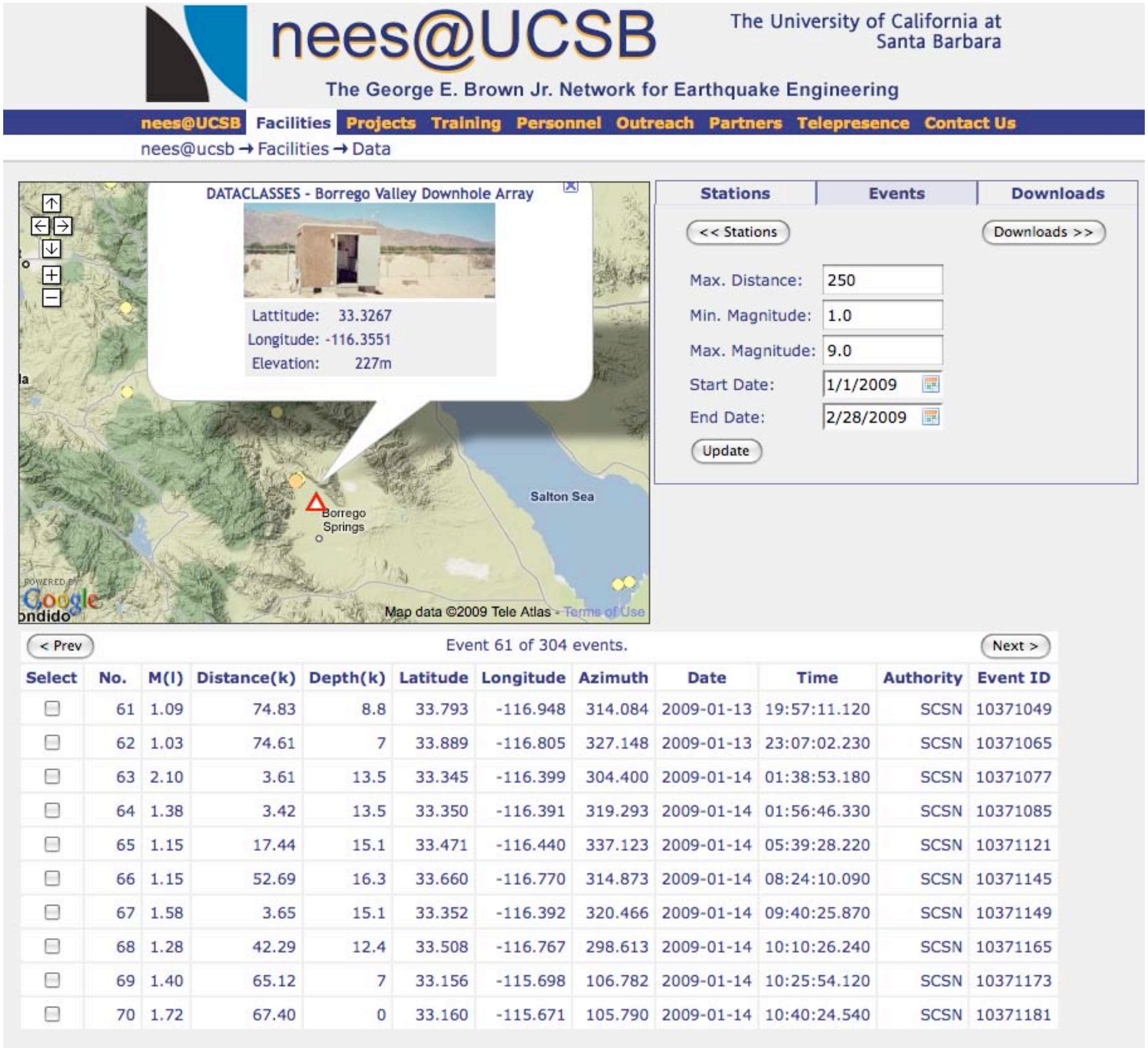


Figure 8. BVDA Vertical Array recordings of a M3.0 at ~15km distance

From the NEES@UCSB website, the search interface currently provides the ability to select a station from a Google Map interface or drop down menu. The available channels are then shown for the particular station, with the ability to select individual channels, or all channels. The Event tab will then provide the ability to search for available events based on magnitude, distance, and time period. The event search returns a list of events with the events also shown on the Google Map interface (Figure 9). After selecting the event, the user can then download individual waveform files, or package a group of files, with the ability to continue to add packages for other events, before downloading all selected packages.

Currently, data is provided in three formats, miniSEED, ASCII (for Excel or MATLAB), and RDV (a variation of ASCII that is meant for the NEES Java based real-time data viewer tool). The miniSEED format is provided in raw counts and is for more advanced users. The ASCII data formats can be provided with calibration applied to physical units, or in raw units by the user. Making other data formats available for dissemination, for example SAC, is under consideration and will depend on user feedback. Tracking mechanisms for the number of waveforms downloaded and the number of users will also be available. Search capabilities using signal-to-noise ratios, peak acceleration, and peak velocity are currently under development. Lastly, the ability to view waveforms and zoom in and out through the web browser are currently under development in a collaboration between the EarthScope Array Network Facility and the NEES program. This web-based waveform viewer should be available in summer 2009. The BVDA data will be incorporated into these developments.



Select	No.	M(l)	Distance(k)	Depth(k)	Latitude	Longitude	Azimuth	Date	Time	Authority	Event ID
☐	61	1.09	74.83	8.8	33.793	-116.948	314.084	2009-01-13	19:57:11.120	SCSN	10371049
☐	62	1.03	74.61	7	33.889	-116.805	327.148	2009-01-13	23:07:02.230	SCSN	10371065
☐	63	2.10	3.61	13.5	33.345	-116.399	304.400	2009-01-14	01:38:53.180	SCSN	10371077
☐	64	1.38	3.42	13.5	33.350	-116.391	319.293	2009-01-14	01:56:46.330	SCSN	10371085
☐	65	1.15	17.44	15.1	33.471	-116.440	337.123	2009-01-14	05:39:28.220	SCSN	10371121
☐	66	1.15	52.69	16.3	33.660	-116.770	314.873	2009-01-14	08:24:10.090	SCSN	10371145
☐	67	1.58	3.65	15.1	33.352	-116.392	320.466	2009-01-14	09:40:25.870	SCSN	10371149
☐	68	1.28	42.29	12.4	33.508	-116.767	298.613	2009-01-14	10:10:26.240	SCSN	10371165
☐	69	1.40	65.12	7	33.156	-115.698	106.782	2009-01-14	10:25:54.120	SCSN	10371173
☐	70	1.72	67.40	0	33.160	-115.671	105.790	2009-01-14	10:40:24.540	SCSN	10371181

Figure 9. Screenshot showing the incorporation of the BVDA site into the NEES@UCSB web-based data dissemination tools.

Conclusions and Future Work:

The project has been successful from the standpoint of the integration of the BVDA field site with the NEES program. The primary goal of installing the Marmot field processor and establishing a link to the automated processing tools developed under the NEES program has been accomplished. Beyond this, the data dissemination tools and all other future NEES software development work will also be directly applicable to the BVDA field site. Future work is planned to integrate the BVDA event waveform database into the MATLAB analysis tools currently under development. This will provide the ability to easily access the event waveform database and perform vertical array seismogram inversions to examine attenuation and site response analysis in the low-strain regime, and eventually the large-strain regime when the Earth decides to cooperate.

Publications:

The general data dissemination tool development has been reported at the 14th World Conference on Earthquake Engineering, and while the BVDA site was not specifically mentioned in this publication, the development tools apply to BVDA as well as the other NEES and non-NEES sites.

Steidl, J. H., R. L. Nigbor, T. L. Youd (2008). Observations of *insitu* soil behavior and soil-foundation-structure interaction at the George E. Brown, Jr. network for earthquake engineering simulation (NEES) permanently instrumented field sites, *Proceedings of the 14th World Conference on Earthquake Engineering, October 12-17, 2008 Beijing, China*, paper S16-01-014.

Once the web-based waveform viewer and event search tools are completed, we plan to submit a Seismological Research Letters manuscript to help publicize the data availability and web-based dissemination tools.

The waveform analysis and seismogram inversion results are still a work in progress. We have been porting the inversion code over to MATLAB so that we can take advantage of the Antelope waveform database interface to MATLAB. This will allow easier and more automated processing and analysis of events in the online waveform database. A paper is in progress related to the site response and attenuation effects at the BVDA site, as well as other geotechnical array sites for publication in Soil Dynamics and Earthquake Engineering or the Bulletin of the Seismological Society of America. . Funding under this program will be acknowledged when this paper is published, and a copy will be provided.